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Control System Design of a Vertical Take-off and Landing Fixed-Wing UAV

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Abstract: In this study, design and implementation of control system of a vertical take-off and landing (VTOL) unmanned aerial vehicle (UAV) with level flight capability is considered. The platform structure includes both multirotor and fixed-wing (FW) conventional aircraft control surfaces; therefore named as VTOL-FW. The proposed method includes implementation of multirotor and airplane controllers and design of an algorithm to switch between them in achieving transitions between VTOL and FW flight modes. Thus, VTOL-FW UAV's flight characteristics are expected to be improved by enabling agile maneuvers, increasing survivability and exploiting full flight envelope capabilities.

Keywords: Aircraft control, autopilot, mathematical modelling, control, PID control, VTOL, UAV.

1. INTRODUCTION

Aerial vehicles have proved their usefulness in military (combat, deployment of units, patrolling, surveillance, reconnaissance, etc.) and civil areas (transport, search and rescue, fire-fighting, etc.) of various applications over a hundred years, while enhancing their capabilities over time, and fulfilling ever-changing mission requirements. UAVs offer a unique set of advantages compared to piloted aircrafts with smaller, safer and lighter platforms. Future UAVs are expected to perform much more extended missions with higher manoeuvrability and higher degrees of autonomy.

Various capabilities like VTOL, hover, level flight and transitions between hover and level flight can be expected from a UAV platform, according to mission requirements. When VTOL and hovering are required, then rotary-wing aircraft such as helicopters, multirotors and ducted fans are most optimal. However, if endurance is of first priority, then a fixed-wing type will most likely be preferred due to efficiency of level flight. When both of these features are desired, then a VTOL-UAV with level flight capability becomes the best option. VTOL capability removes the need for runway or launch/recovery equipment and provides flexibility to operate in any theatre, whereas level flight capability allows efficient range and endurance flight. An aerial vehicle designed to possess the strengths of both a rotary and fixed-wing aircraft will have both of the advantageous in one platform.

Transition manoeuvres between hover and level flight is of primary concern for VTOL aircrafts that are capable of level flight. T-wing tailsitter UAV with two counter rotating propellers was one of the pioneering studies; Stone (2004a and 2006b) has developed a flight control system including low-level and mid-level guidance controllers, utilizing linear quadratic regulator and classical controllers, which were verified in flight tests by Anderson et al. (2008). Kubo (2006) showed that a tailsitter UAV could achieve transitions between level flight and hover in shorter time using slats and flaps by using an optimal controller. Hogge (2008) demonstrated transition manoeuvres of a UAV with only one propulsion system using control surfaces. Tumble-stall manoeuvres are implemented in achieving transitions by Green (2005), Anathkrishnan (2008) and Jung (2010) utilizing dynamic inversion methods. A state machine is designed by Osborne (2007) and Çakıcı (2011) for transitions between the flight modes, where the states were defined as hover, level, hover-to-level and level-to-hover. Backstepping control technique is studied by Wang et al. (2008) for a coaxial-rotor tailsitter UAV and successfully simulated hover, level flight and transitions. Although available studies in this field are successfully implemented on different platform types, an aircraft that has physically separated multirotor and airplane control surfaces is not examined in demonstrating transition manoeuvres.

In this study, design and implementation of control system of a VTOL aircraft with level flight capability is considered. The proposed method includes implementation of multirotor and airplane controllers and design of an algorithm to switch between them in achieving transitions between VTOL and FW flight modes. Thus, VTOL-FW UAV's flight characteristics are expected to be improved by enabling agile manoeuvres, increasing survivability, providing redundancy and exploiting full flight envelope capabilities.

2. VTOL-FW UAV PLATFORM

VTOL-FW UAV platform (Fig. 1) is constructed by multirotor modification of a model airplane. Then, the platform is converted into an UAV by adding an autonomous flight controller (Pixhawk) and sensors like GPS, magnetometers, accelerometers, gyros, pitot-static system as in Çakıcı et al. (2015).

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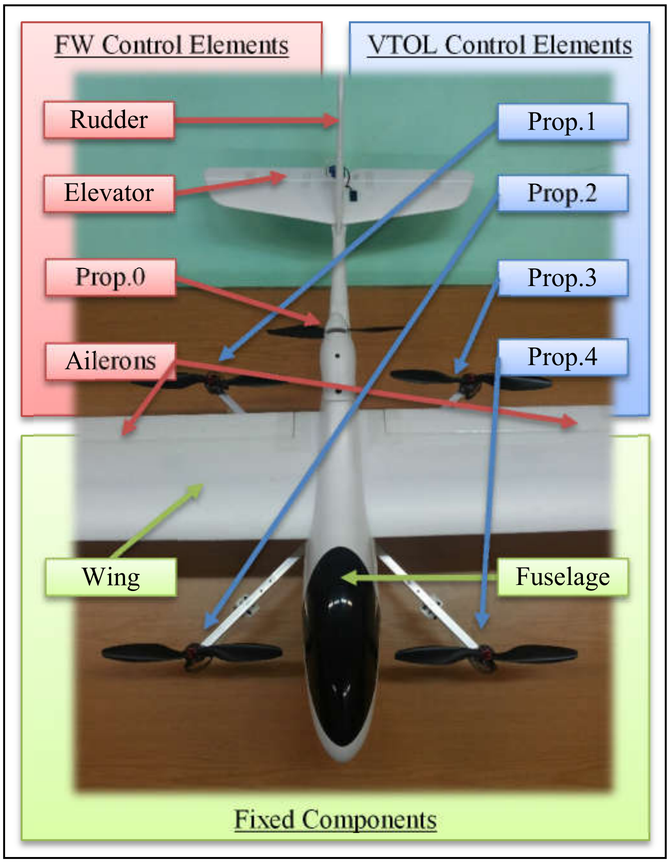

Fig. 1. Control elements of VTOL-FW UAV.

Main components of the aircraft contributes to forces and moments acting on the vehicle in flight. Fuselage causes drag in negative direction of airflow, caused by motion. FW propulsion system (Prop.0) provides thrust to balance drag, while main wing provides lift to overcome gravitational force and ailerons, rudder and elevator provide roll, pitch and yaw motions as in a conventional airplanes. VTOL propulsion systems (Prop.1-4) provide lift, roll, pitch and yaw motions by changing the rotational speeds of the propellers, as in a multirotor.

Flight mode of VTOL-FW UAV is determined according to vertical and horizontal velocities of the aircraft in full flight envelope (Fig. 2), that covers both VTOL and FW regions. When both of the vertical and horizontal velocities are small in magnitude, the aircraft operates in VTOL mode with VTOL control elements activated. As horizontal velocity is increased the aircraft enters the FW mode by enabling FW control elements. Intersectional region is used for switching between VTOL and FW modes, by changing active control elements.

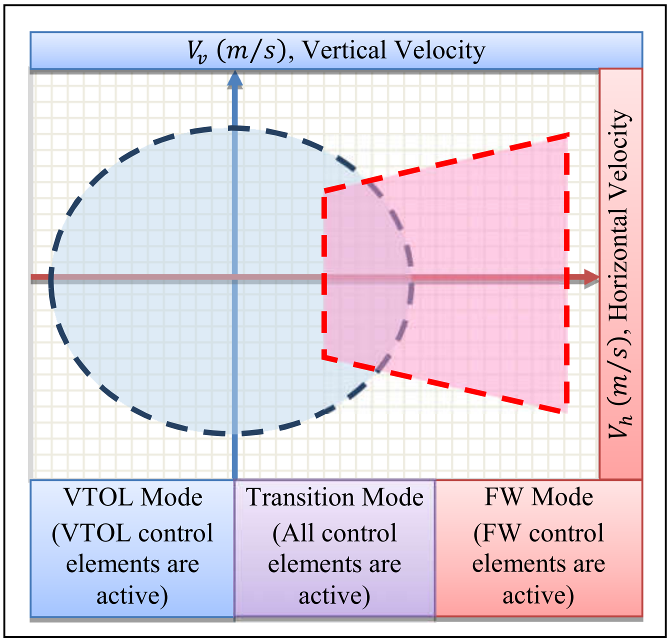

Fig. 2. Flight envelope of VTOL-FW UAV.

3. MATHEMATICAL MODELLING

The complexity of dynamics of aerial vehicles, makes obtaining accurate mathematical models for a large portion of flight envelope a difficult problem. VTOL-FW UAV platform is modelled by using the real physical specifications of the aircraft in a MATLAB graphical user interface (Fig. 3) environment that is specifically developed for the initial design, analysis, control system design, mission planning and flight simulations of aircrafts. Initially, every main component like fuselage, wings, control surfaces and propellers are modelled using aerodynamical principles stated by McRuer (1973), Leishman (2006), Allerton (2009) and Çakıcı (2009), for the whole flight envelope including post-stall conditions. Then, these model's outputs are combined considering aircraft's geometry in calculating total forces and moments. Equations of motion, defined by Craig (1989), are formed as a set of nonlinear equations (1), using Newton's 2nd law of forces, Euler's formula for moments and kinematic relationships defined in body frame.

$$\dot{x} = f(x,u,t) \tag{1}$$

where x: state variables, u: control variables, t: time.

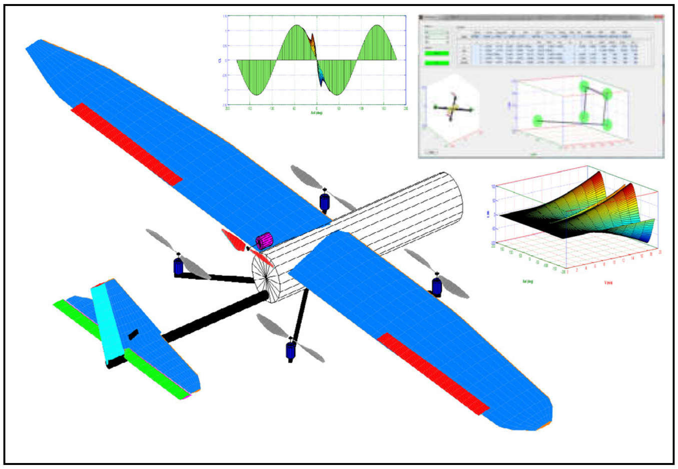

Fig. 3. Model of VTOL-FW UAV.